What Can We Learn From Simulations of Tilted Black Hole Accretion Disks?

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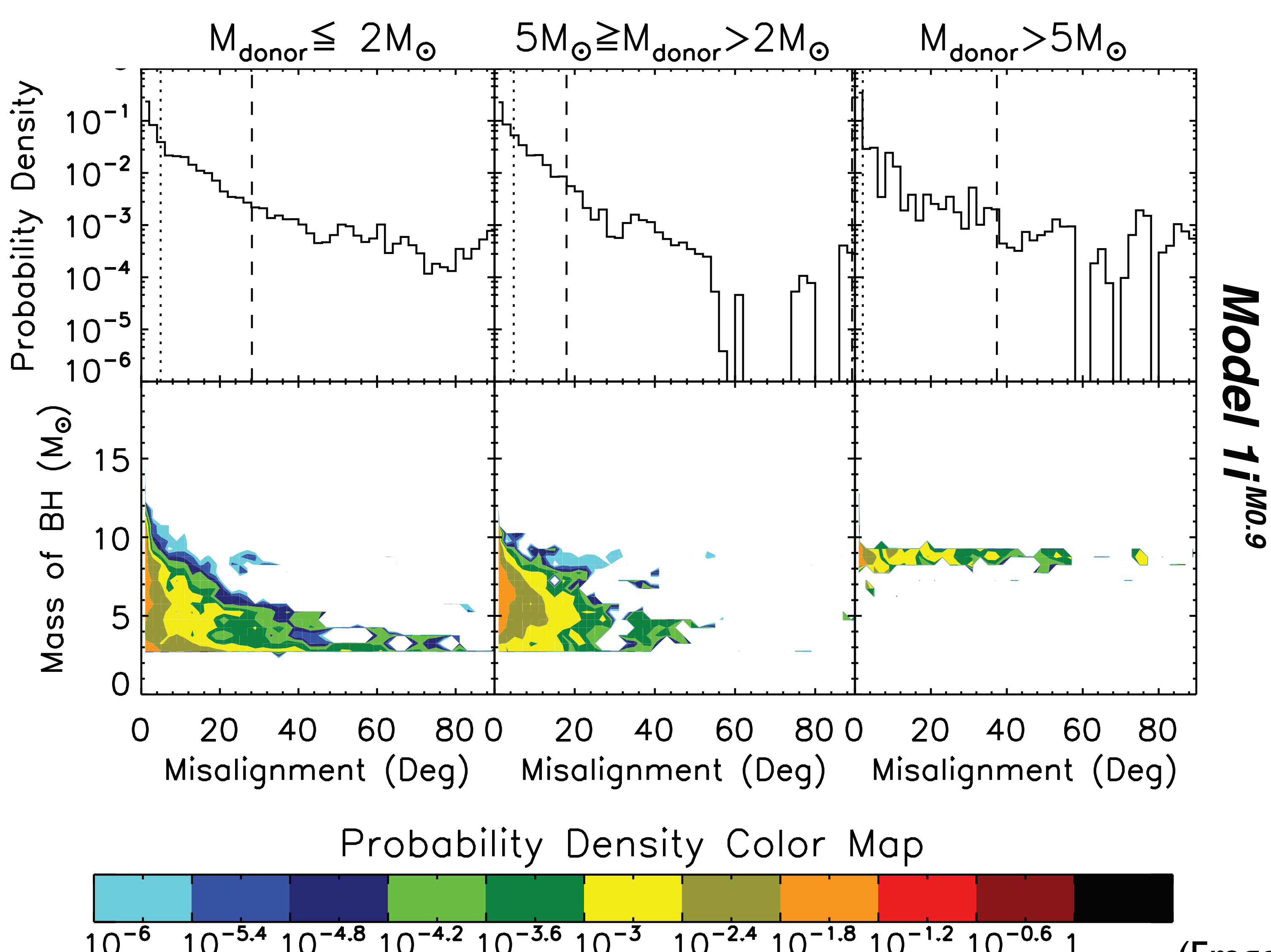
Astrophysical motivation

- Active Galactic Nuclei (AGN)
  - Post merger
- Black hole X-ray Binaries (BHXRB's)
  - Asymmetric supernova kick



(Fragos et al. 2010)

Simulations of tilted disks

- Initialization similar to model KDP from DeVilliers, Hawley, & Krolik (2003)
- Initial tilt (15°) added

$$128^3$$

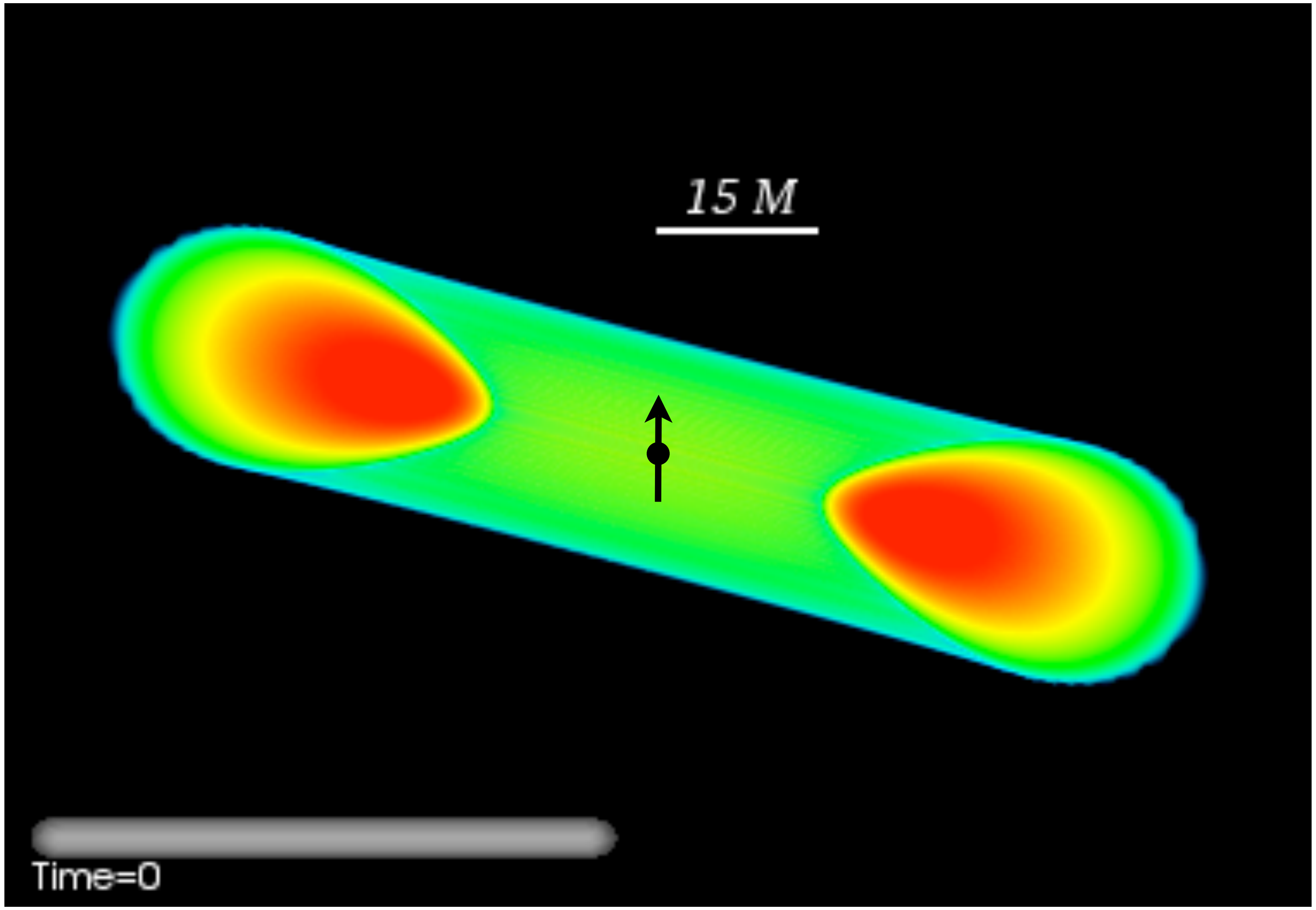
$$\Gamma = 5/3$$

$$r_{P_{\max}} = 25 r_G$$

$$r_{\rm in} = 15 r_G$$

$$a_* = 0.9$$

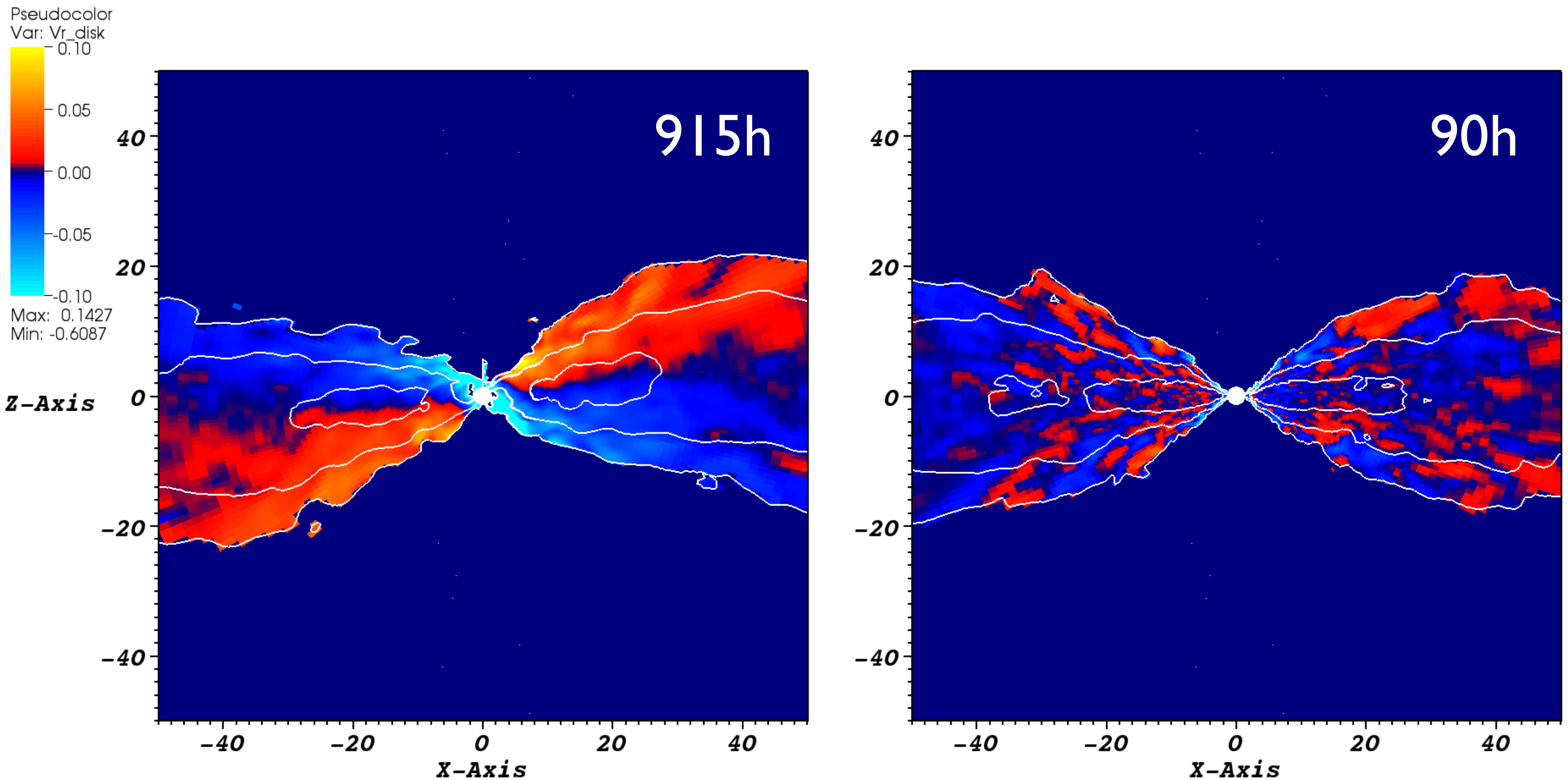
$$\beta_0 = 15^\circ$$



http://fragilep.people.cofc.edu/research/movies/torus3d.m.915h_rho.mov

Tilted Black Hole Accretion Disks

Epicyclic motion induced by tilt



Fragile & Blaes (2008)

Tilted Black Hole Accretion Disks

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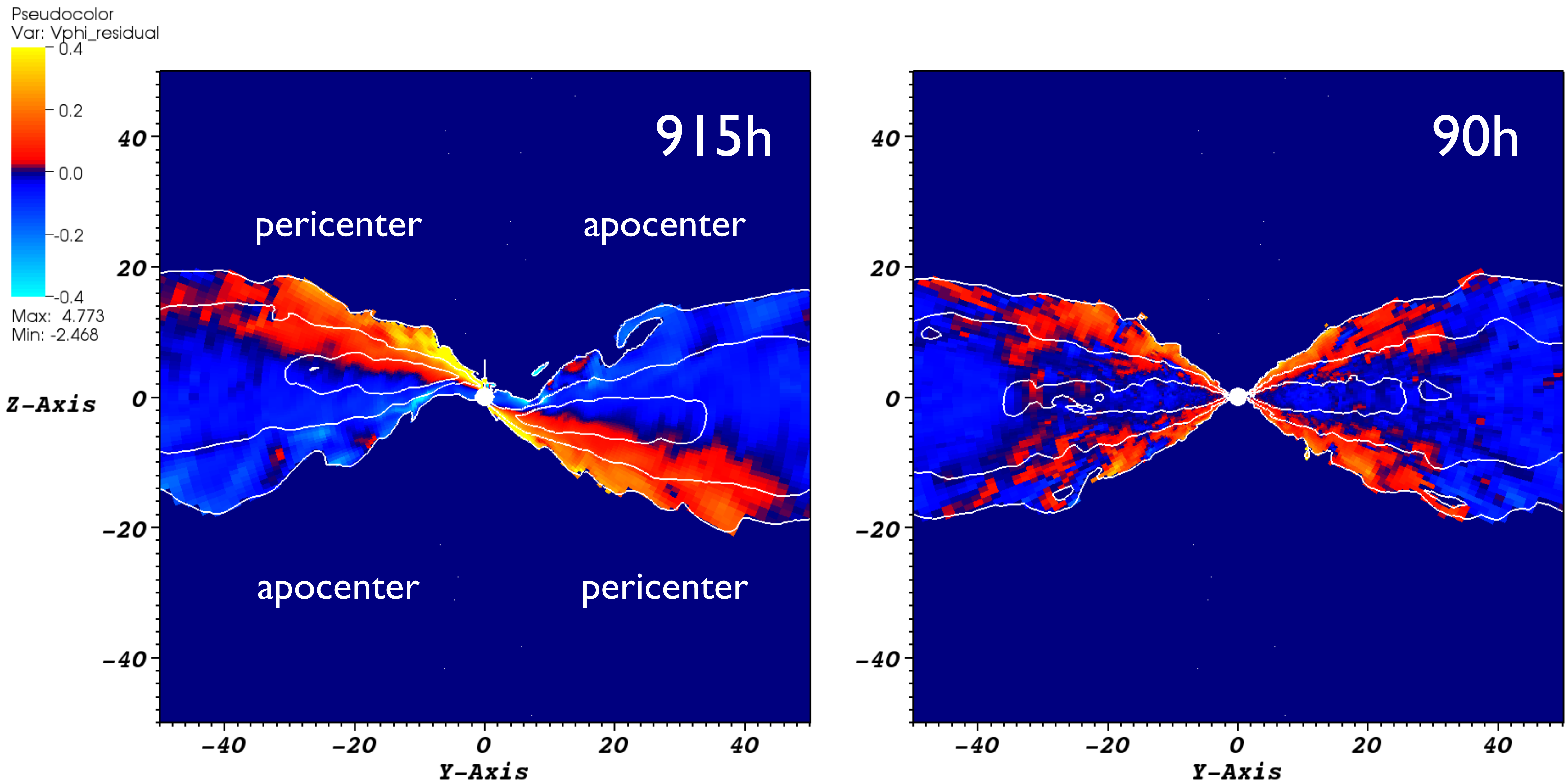


Fragile & Blaes (2008)

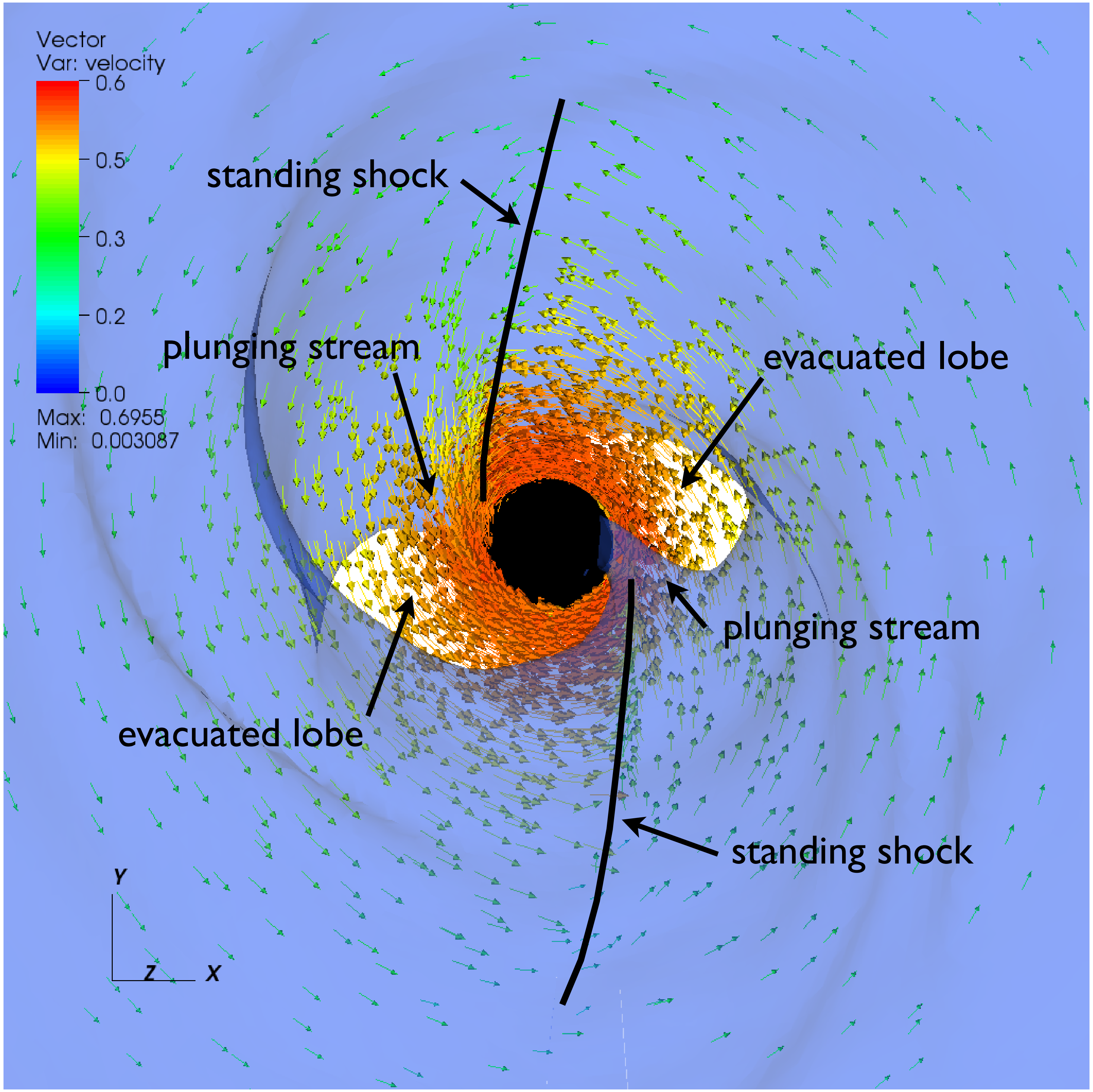
Tilted Black Hole Accretion Disks

Take-away points

1. Global radial epicyclic motion
    - 180° out of phase across the midplane

Tilted Black Hole Accretion Disks

Standing shocks

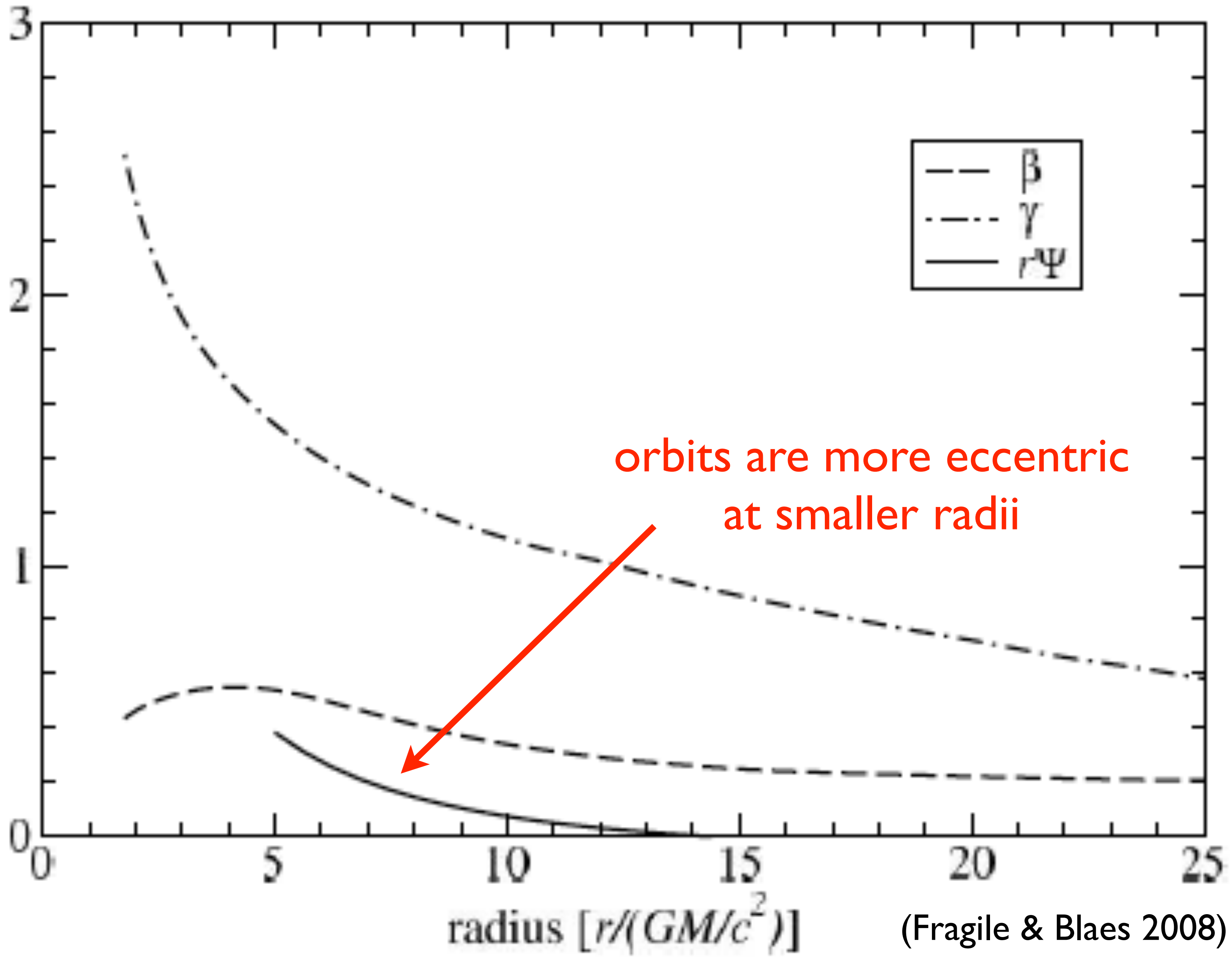


(Fragile & Blaes 2008)

Eccentricity of tilted orbits

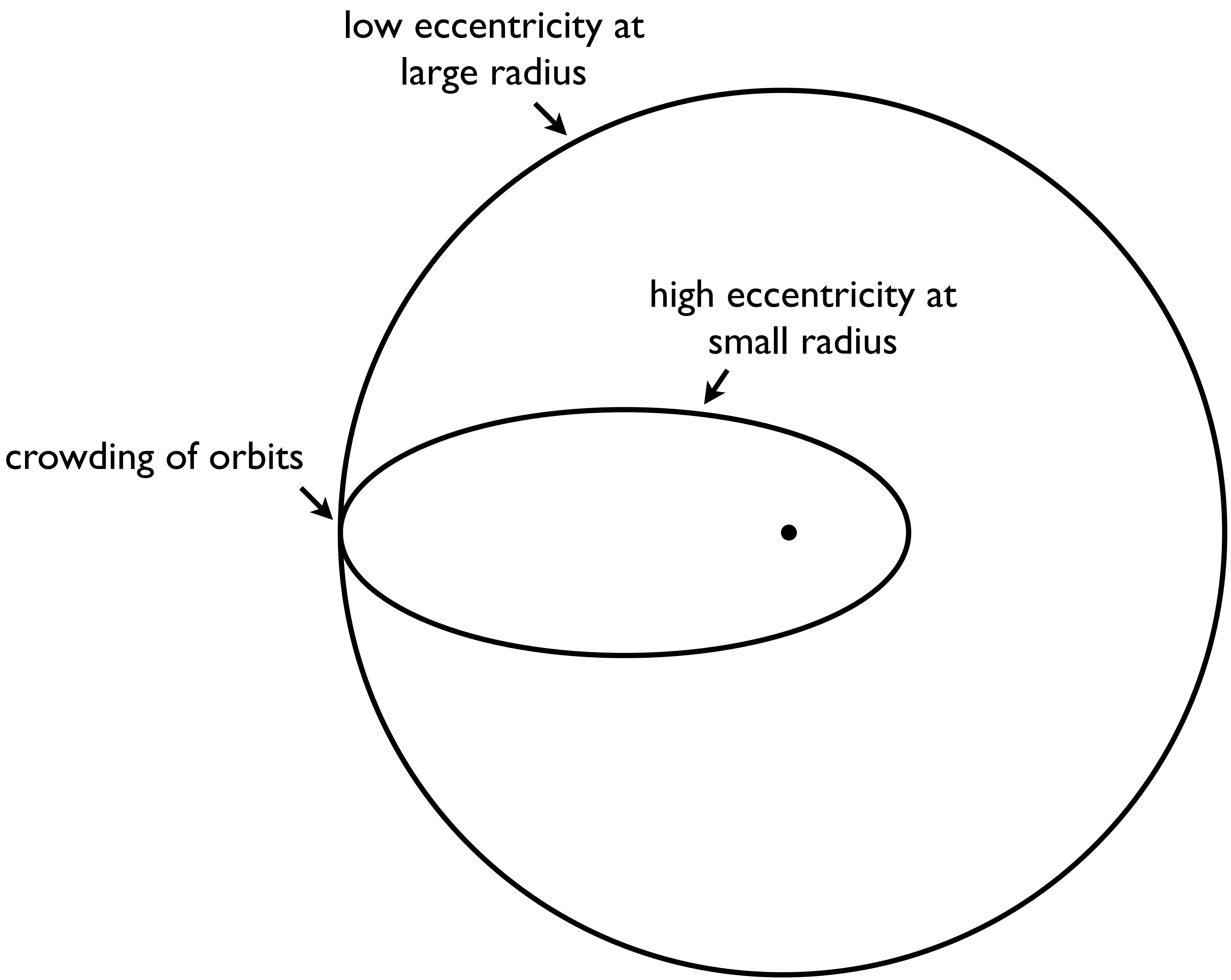
- In terms of "twisting" coordinates (R, ψ, ξ)

$$e = \frac{\xi}{6M} R\Psi = \frac{\xi}{6M} R \frac{\partial(\beta \cos\gamma)}{\partial R}$$

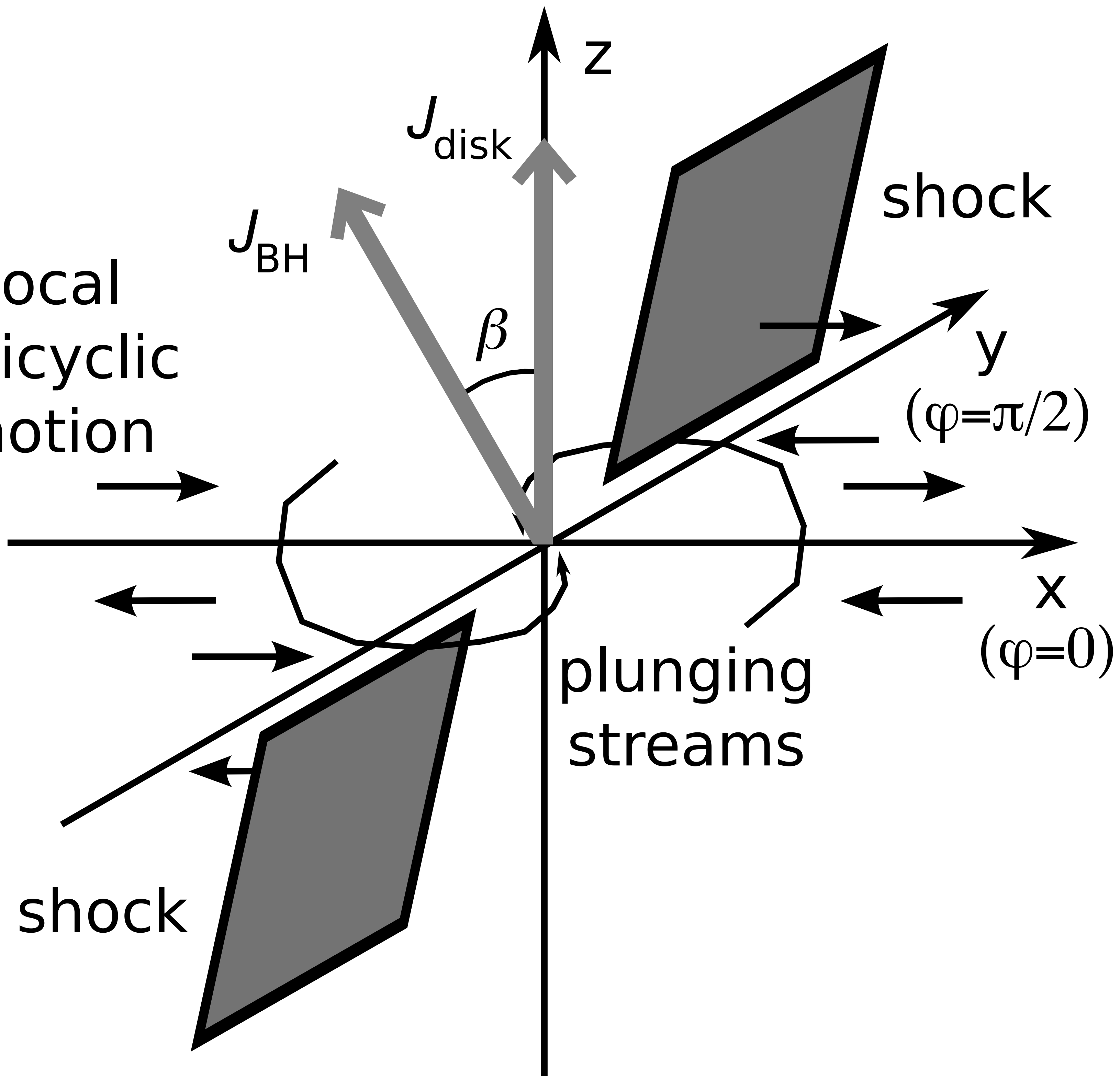


(Fragile & Blaes 2008)

Crowding of orbits near apocenter



Schematic diagram of results



Take-away points

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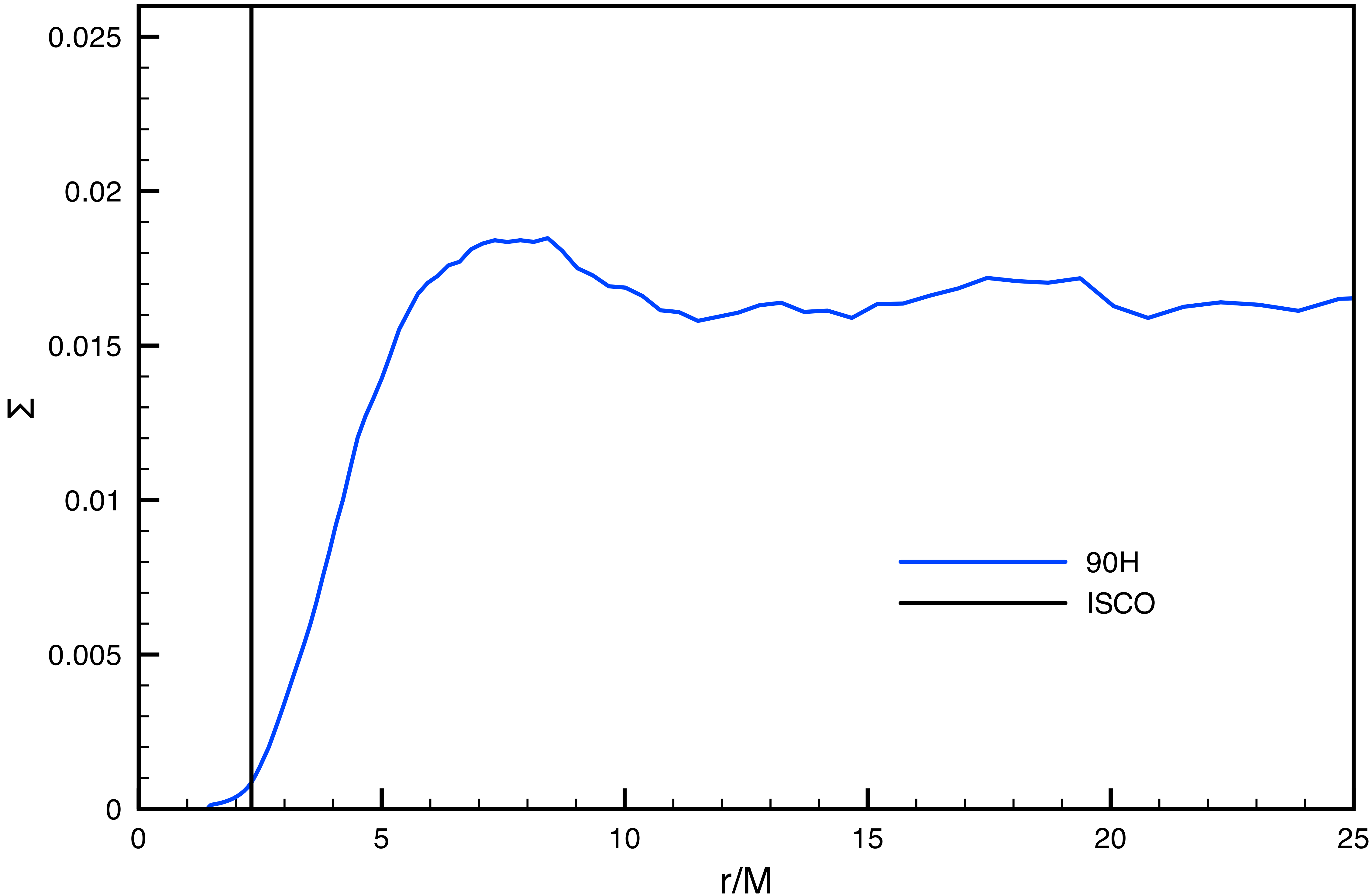
   - 180° out of phase across the midplane
2. Standing shocks near apocenters of orbits
   - One above and one below midplane
   - Aligned with line-of-nodes

Inner radius of tilted disks

- Surface density



Inner radius of tilted disks

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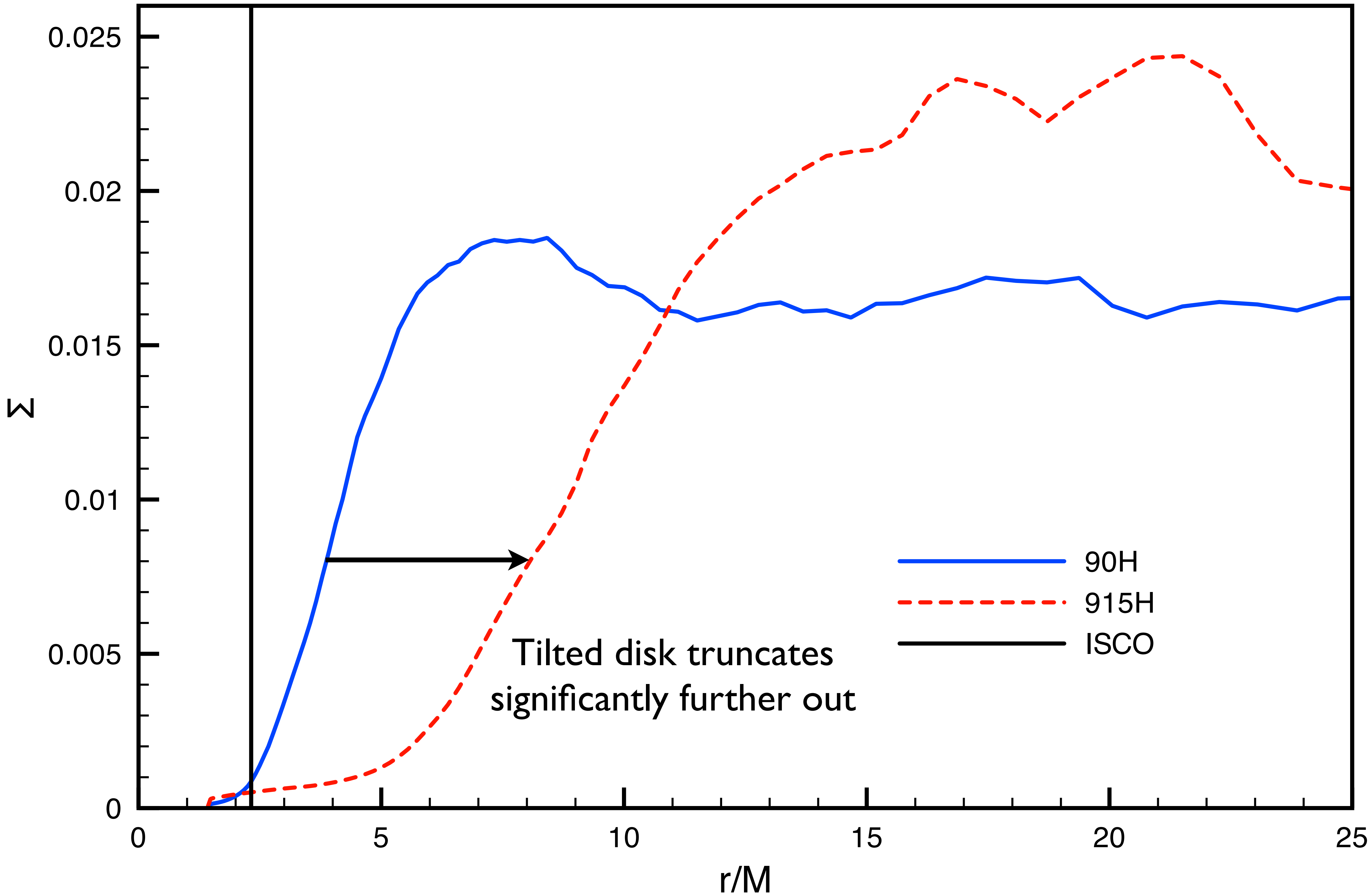
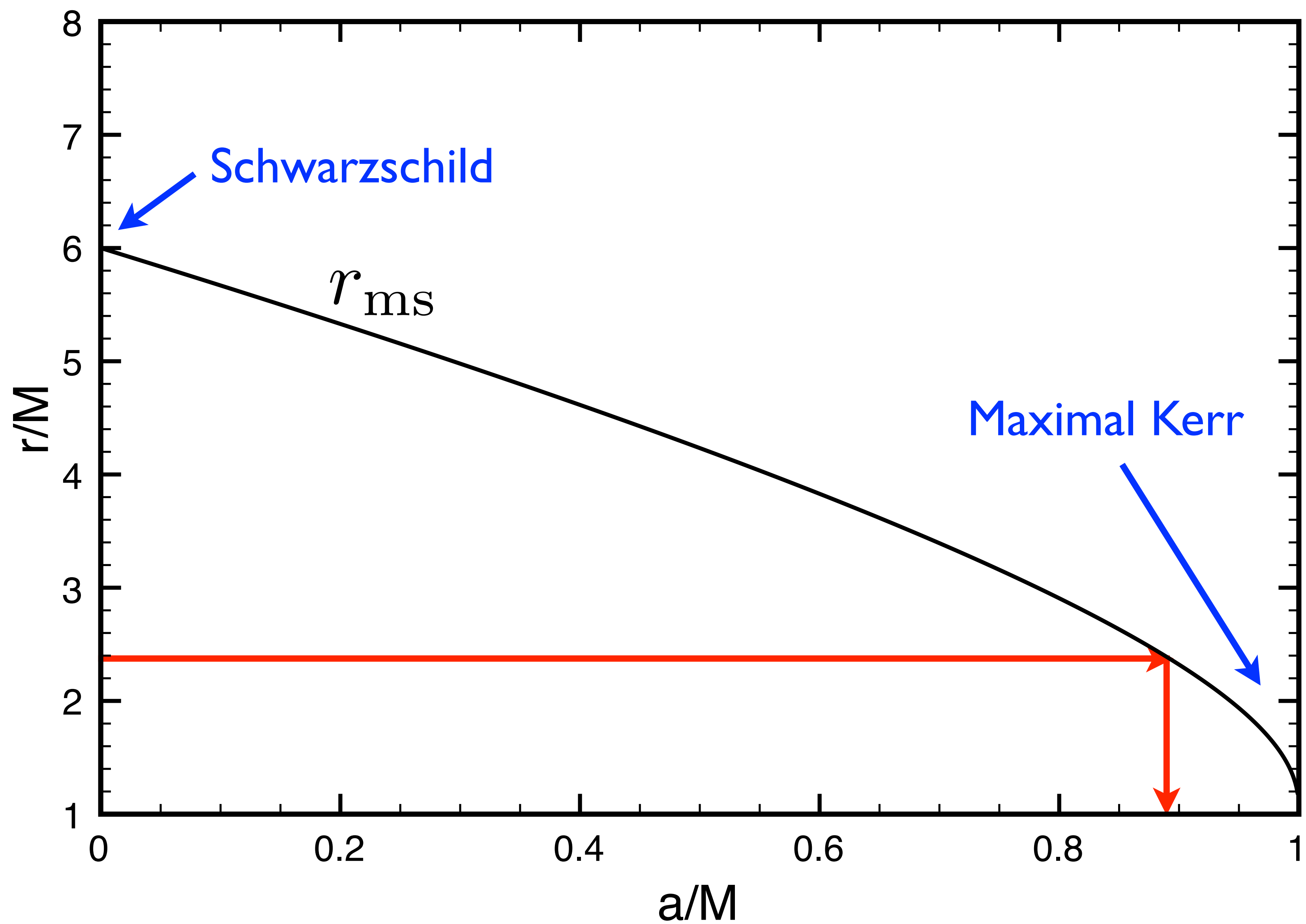


Determining spin of a black hole

- If $r_{\rm in}$ can be measured
  - continuum fitting
  - Fe α line
- If $r_{\rm in} = r_{\rm ms}$

} can get a directly



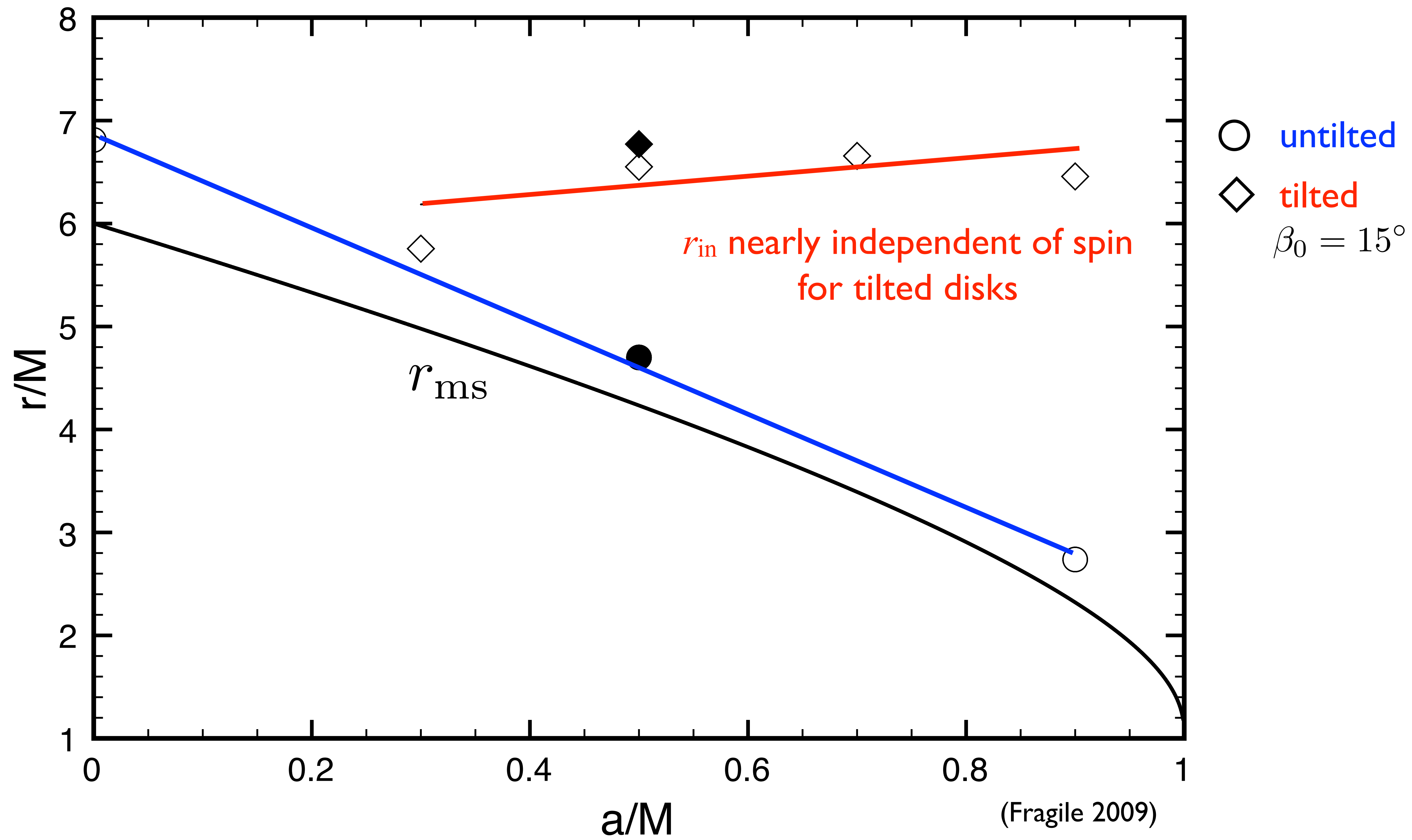
Inner radius of tilted disks

Simulation Parameters			
Simulation	a/M	Tilt Angle	Grid
0H[a]	0	...	Spherical-polar
315H[b]	0.3	15°	Spherical-polar
50H[a]	0.5	0°	Cubed-sphere
515H-S[a]	0.5	15°	Spherical-polar
515H-C[a]	0.5	15°	Cubed-sphere
715H[b]	0.7	15°	Spherical-polar
90H[c]	0.9	0°	Spherical-polar
915H[c]	0.9	15°	Spherical-polar

[a]Fragile, Lindner, Anninos & Salmonson, 2009, ApJ, 691, 428
[b]Fragile, 2009, ApJ, 706, L246
[c]Fragile, Blaes, Anninos & Salmonson, 2007, ApJ, 668, 417

Inner radius of tilted disks

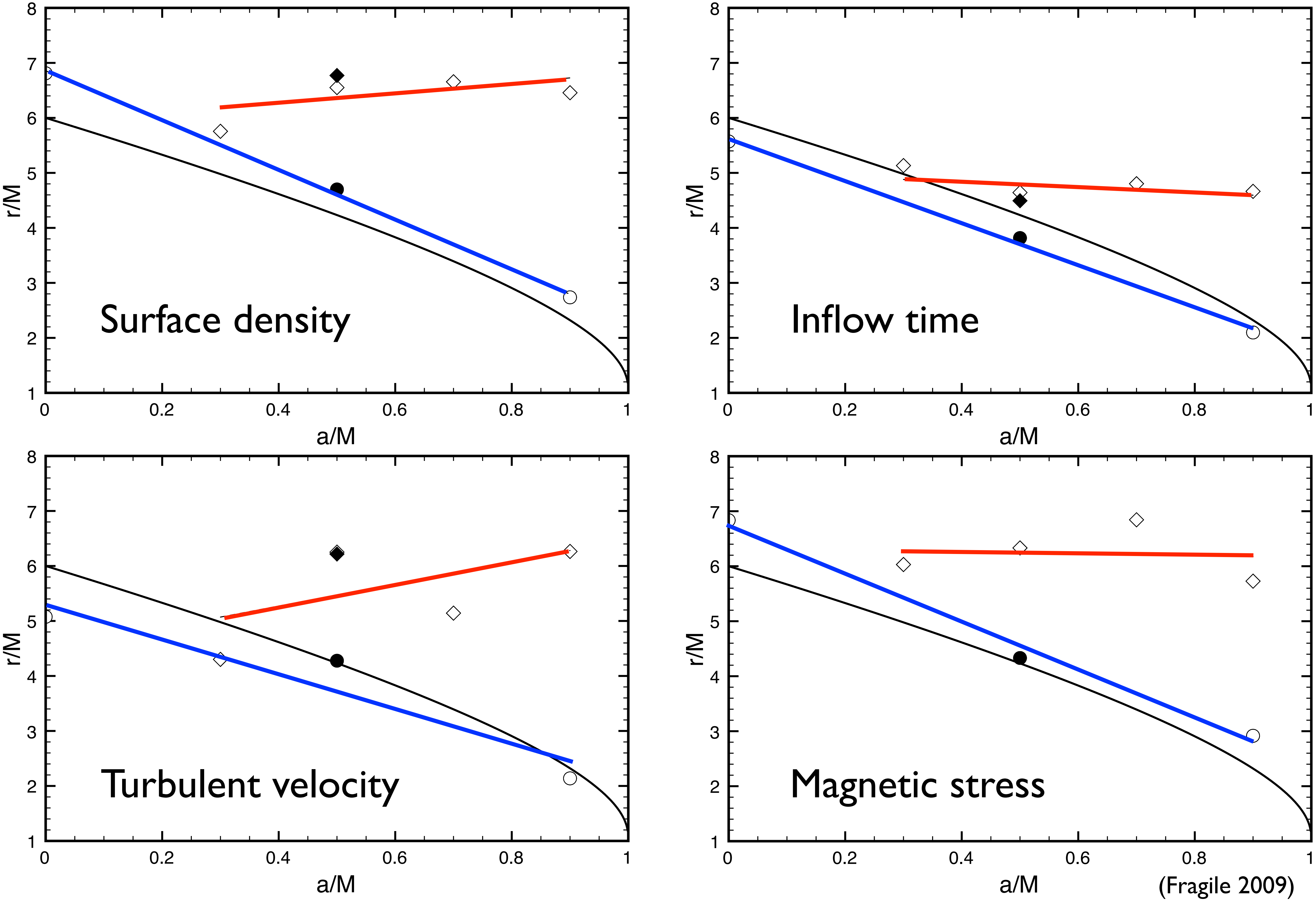
$$\Sigma(r_{\rm in}) = \Sigma_{\rm max}/3e$$



(Fragile 2009)

Tilted Black Hole Accretion Disks

Inner radius of tilted disks



(Fragile 2009)

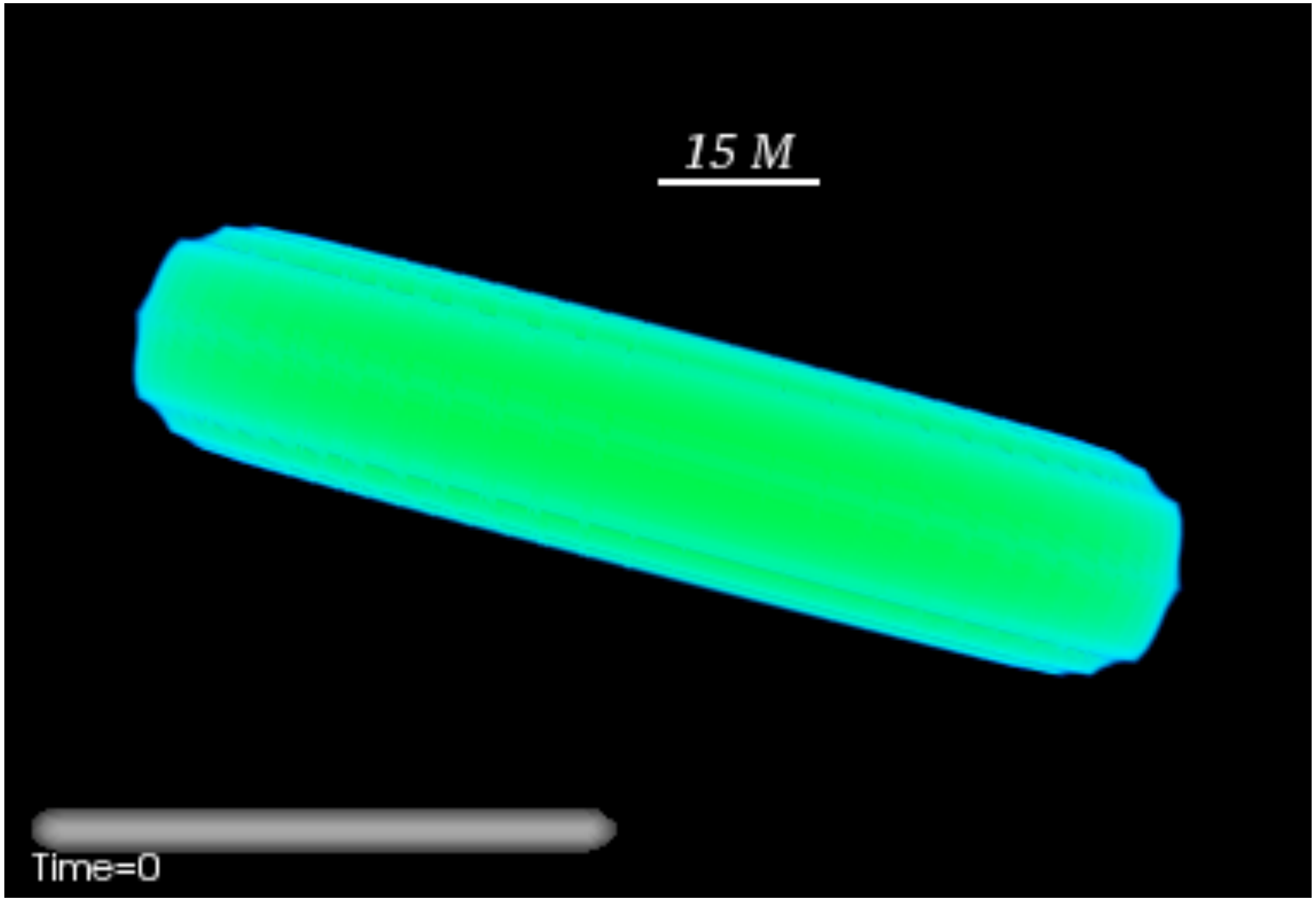
Take-away points

1. Global radial epicyclic motion
   - 180° out of phase across the midplane
2. Standing shocks near apocenters of orbits
   - One above and one below midplane
   - Aligned with line-of-nodes
3. $r_{\rm in}$ nearly independent of spin for tilted disks
   - at least for simulated disks with $H/r \sim 0.2$ and $\beta_0 = 15^\circ$

Tilted Black Hole Accretion Disks

Disk precession

- Torque of BH causes disk to precess
  - After initial twisting phase, disk precesses as solid body



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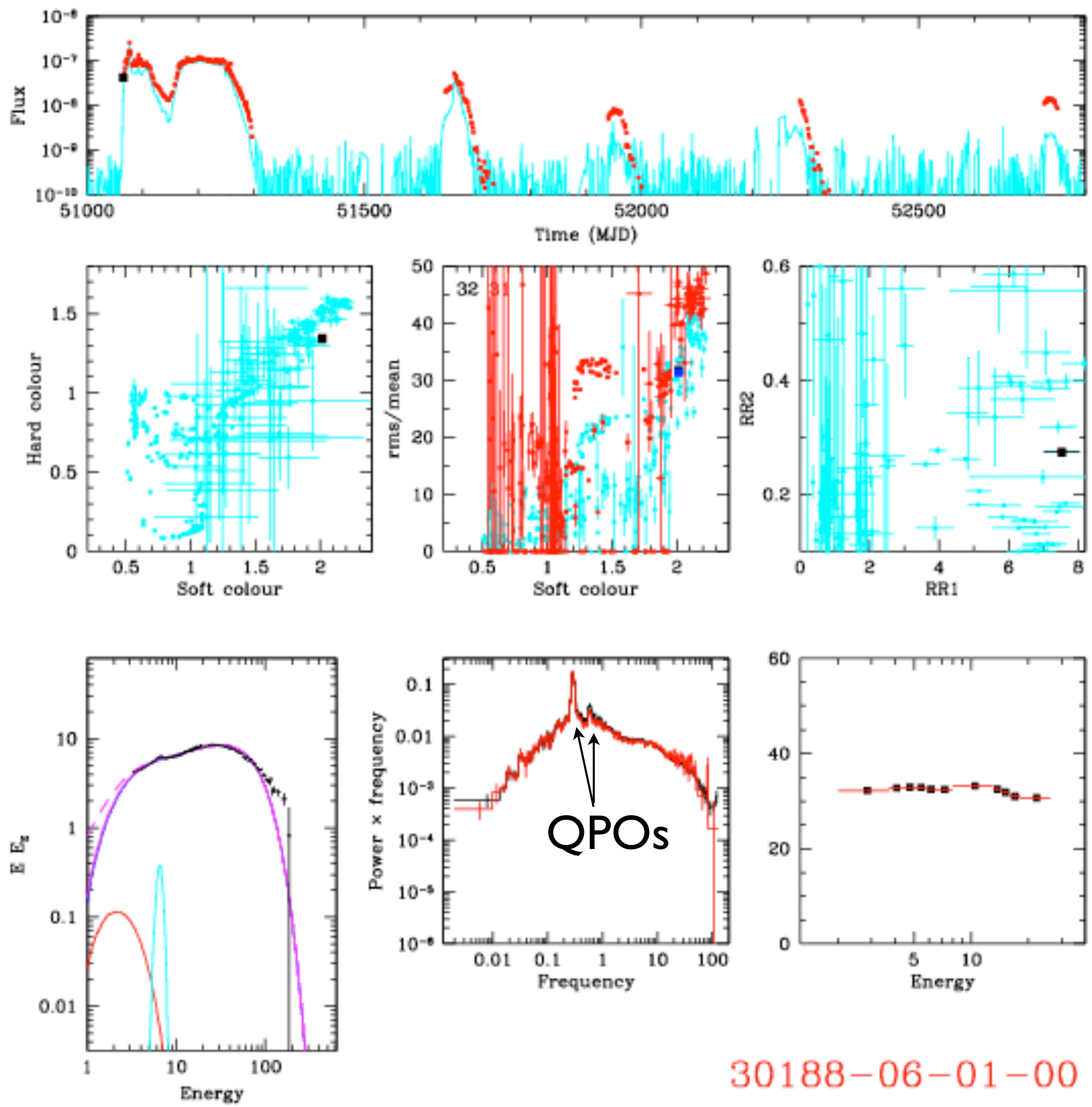
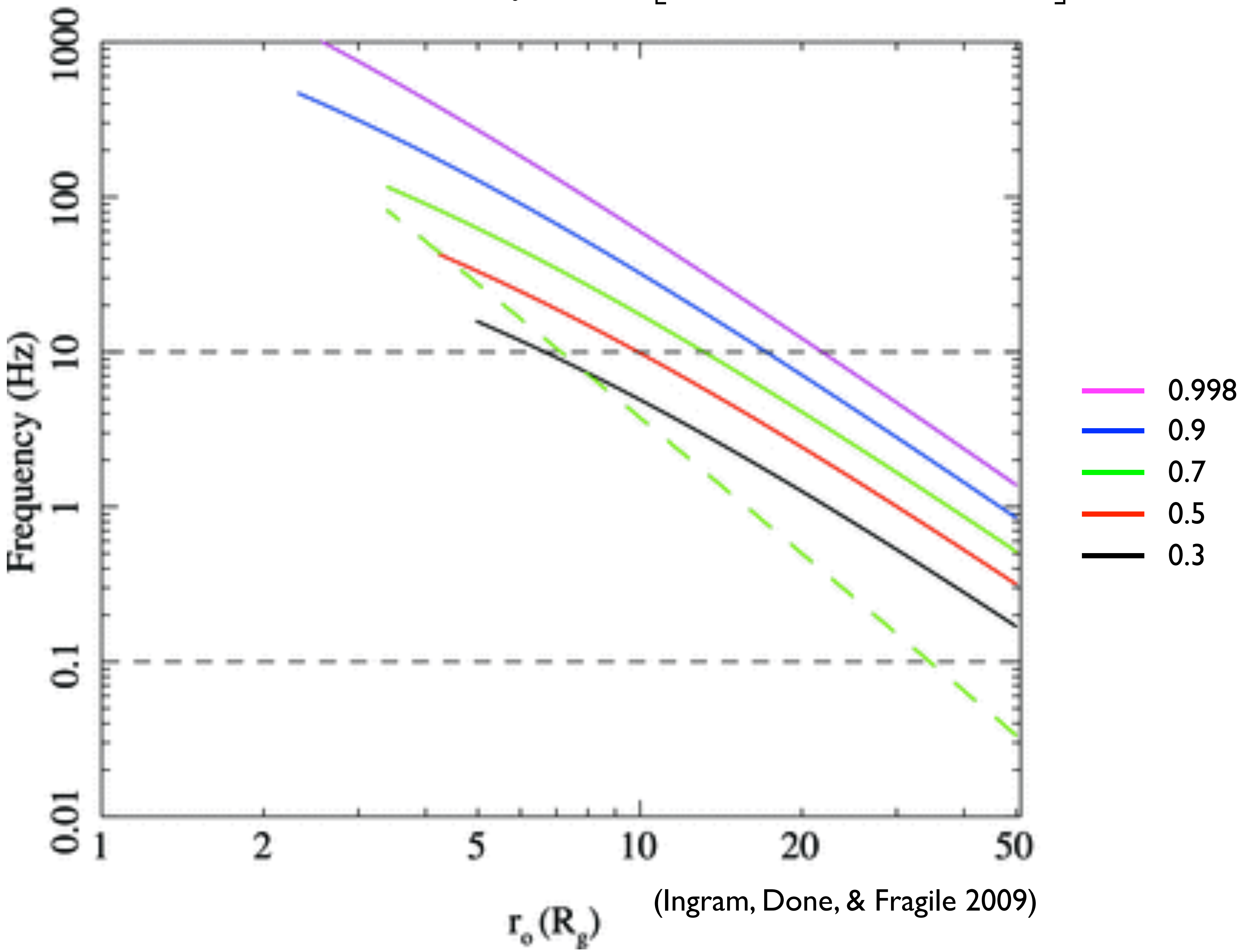
Low Frequency QPOs

XTE J1550-564



LFQPOs from tilted disks

$$\nu_{prec} = \frac{(5-2\zeta)}{\pi(1+2\zeta)} \frac{a_* \left[1-(r_i/r_o)^{1/2+\zeta}\right]}{r_o^{5/2-\zeta} r_i^{1/2+\zeta} \left[1-(r_i/r_o)^{5/2-\zeta}\right]} \frac{c}{R_g}$$



(Ingram, Done, & Fragile 2009)

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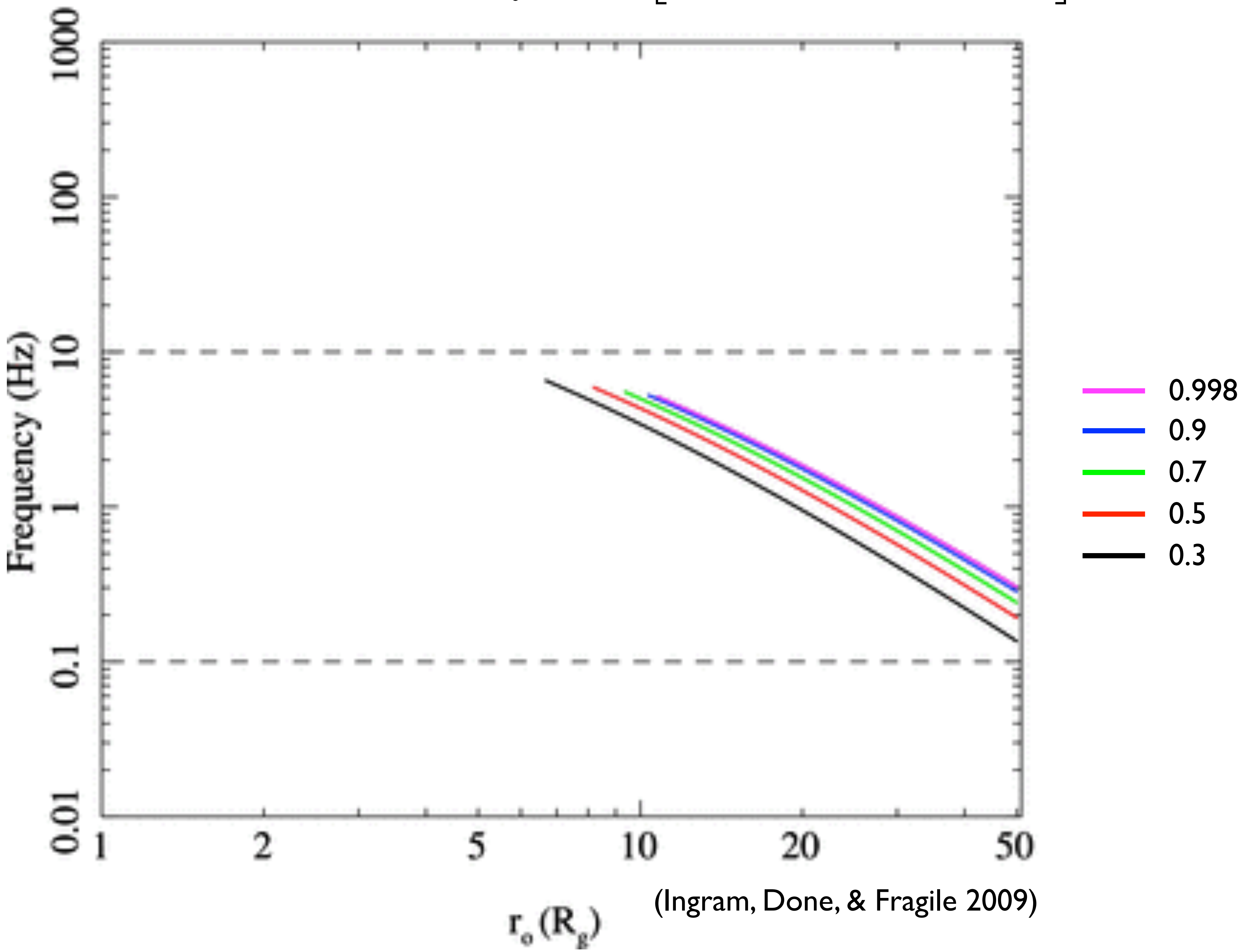

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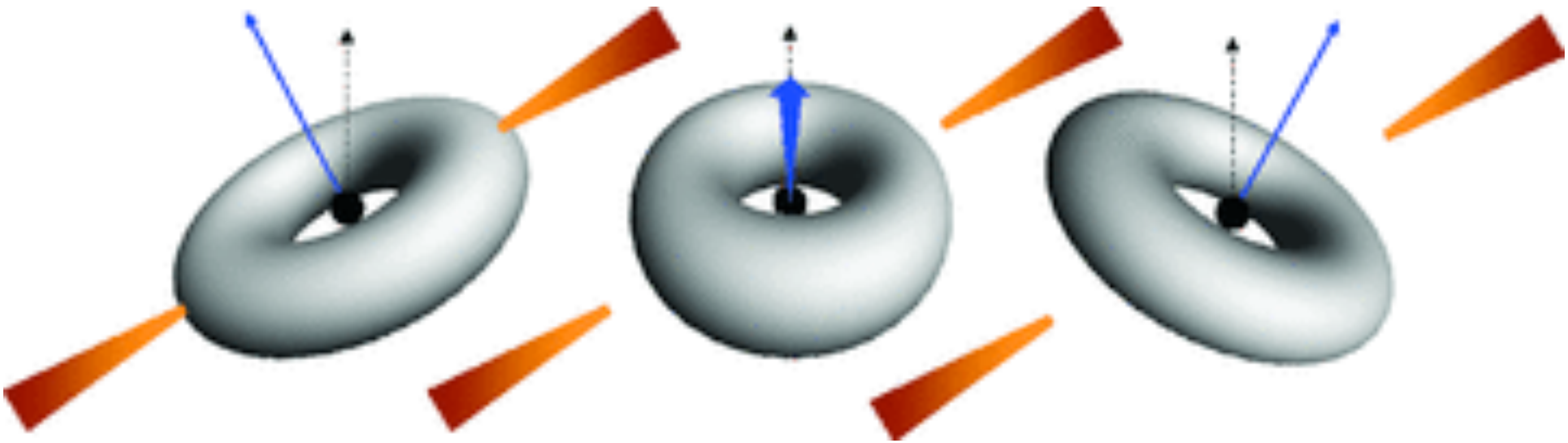
Tilted Black Hole Accretion Disks

LFQPOs from tilted disks



(Ingram, Done, & Fragile 2009)

- How is the hot, thick inner disk coupled to the cold, thin outer disk?
  - Can the inner disk precess freely as assumed in our naive picture?

Take-away points

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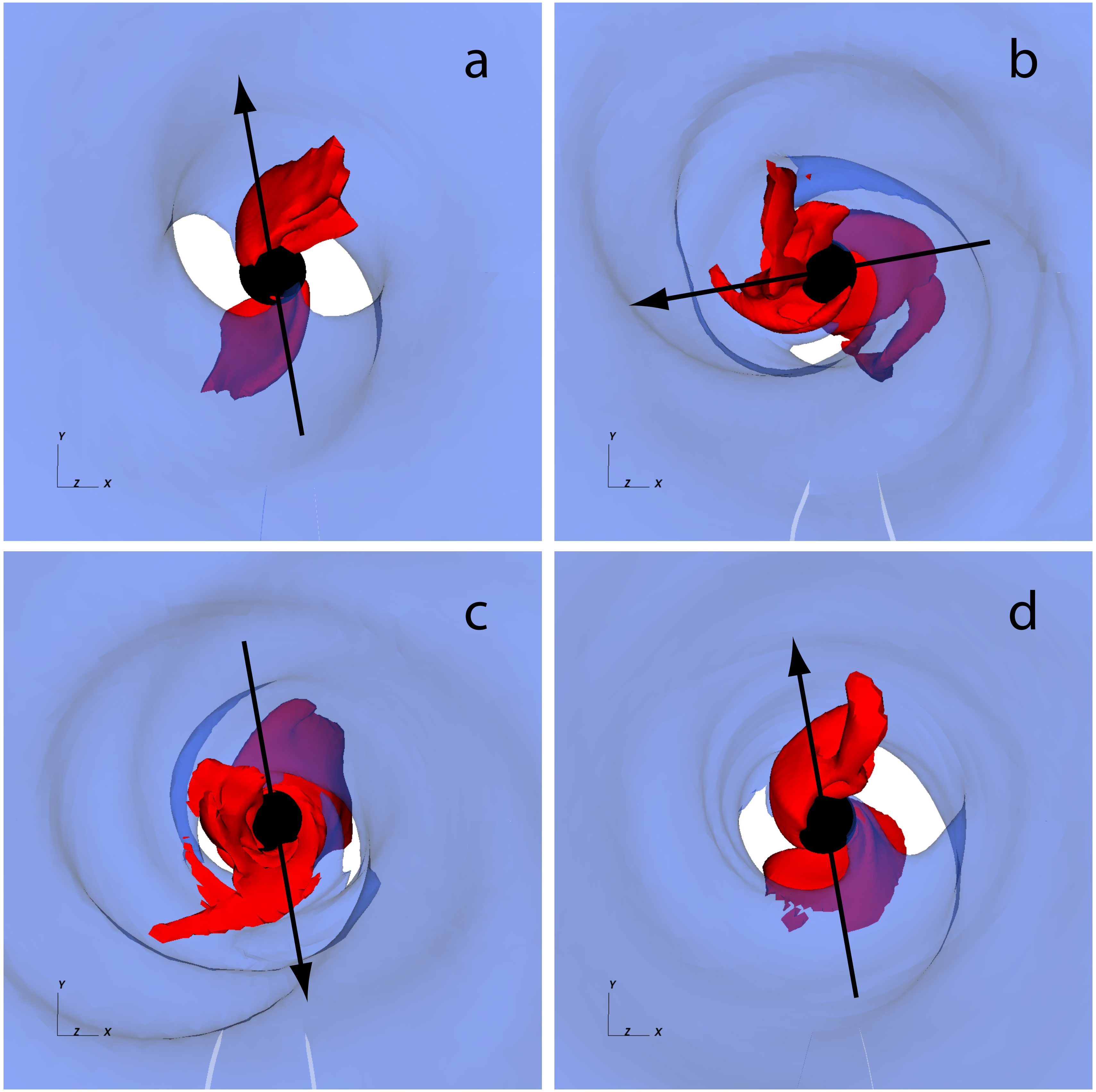
   - 180° out of phase across the midplane
2. Standing shocks near apocenters of orbits
   - One above and one below midplane
   - Aligned with line-of-nodes
3. $r_{\rm in}$ nearly independent of spin for tilted disks
   - at least for simulated disks with $H/r \sim 0.2$ and $\beta_0 = 15°$
4. precessing tilted disks provide a possible model for low-frequency QPOs
   - give right frequency range for large range of black hole parameters

Tilted Black Hole Accretion Disks

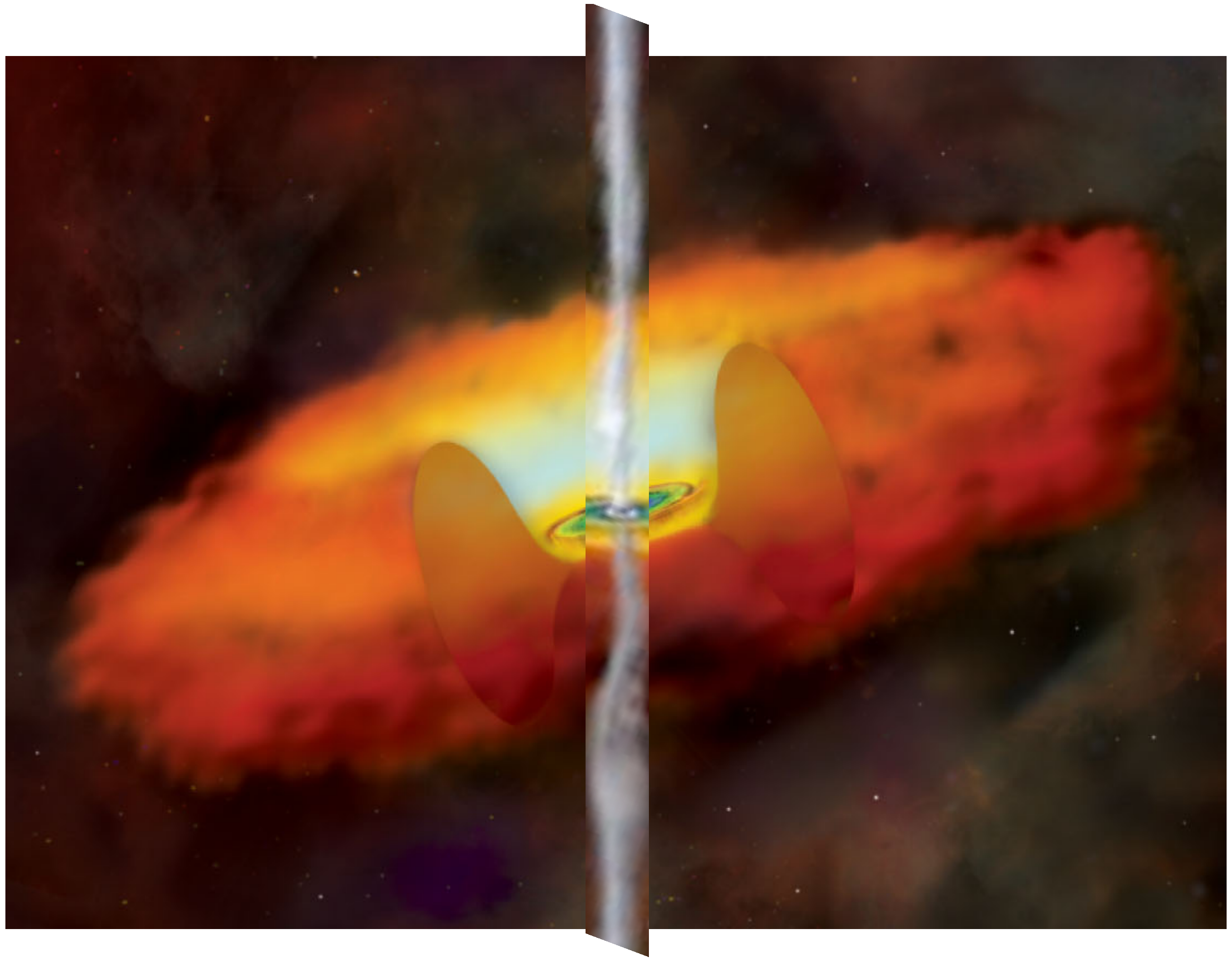
Standing shocks precess with disk



(Fragile & Blaes 2008)

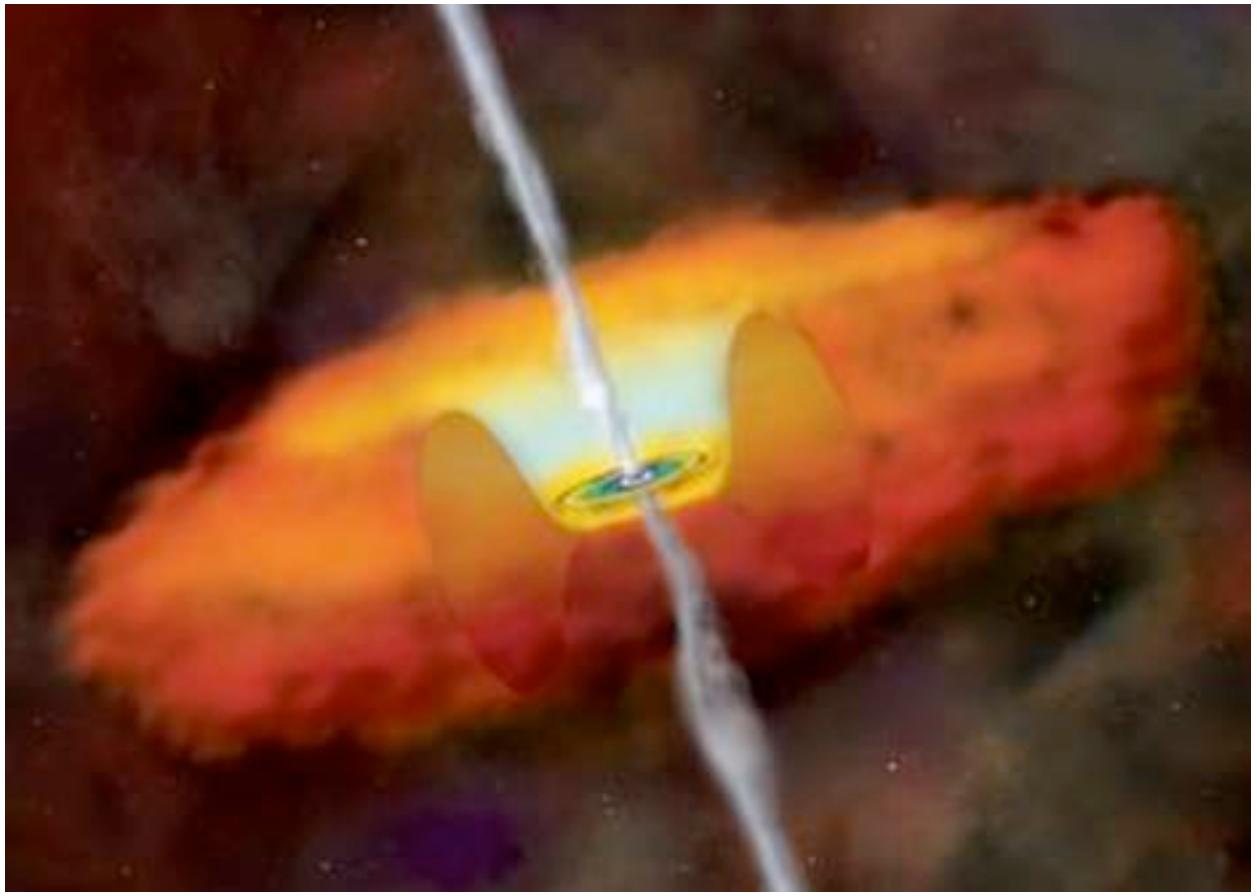
Jet orientation

- What determines the orientation of a jet?
  - angular momentum (spin) of BH (Blandford & Znajek, 1977; Koide et al., 2002)
    - ⊥ to BH symmetry plane



Jet orientation

- What determines the orientation of a jet?
  - angular momentum (spin) of BH (Blandford & Znajek, 1977; Koide et al., 2002)
    - $\perp$ to BH symmetry plane
  - angular momentum or net magnetic flux of disk (Blandford & Payne, 1982; Lynden-Bell, 2006)
    - $\perp$ to disk midplane
    - precess with disk



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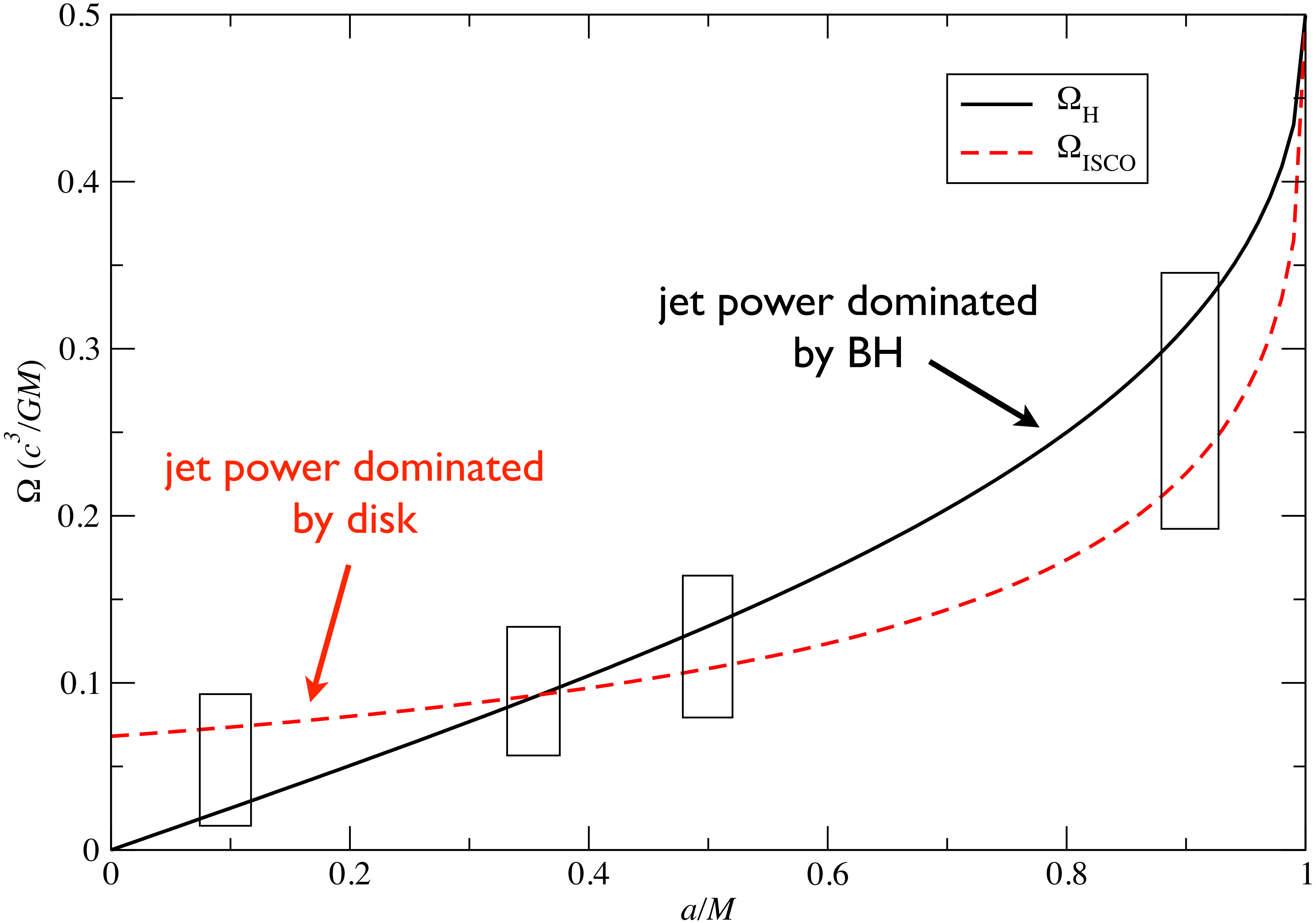
    - ⊥ to BH symmetry plane
  - angular momentum or net magnetic flux of disk (Blandford & Payne, 1982; Lynden-Bell, 2006)
    - ⊥ to disk midplane
    - precess with disk
  - properties of ambient medium
    - ????

Jet orientation

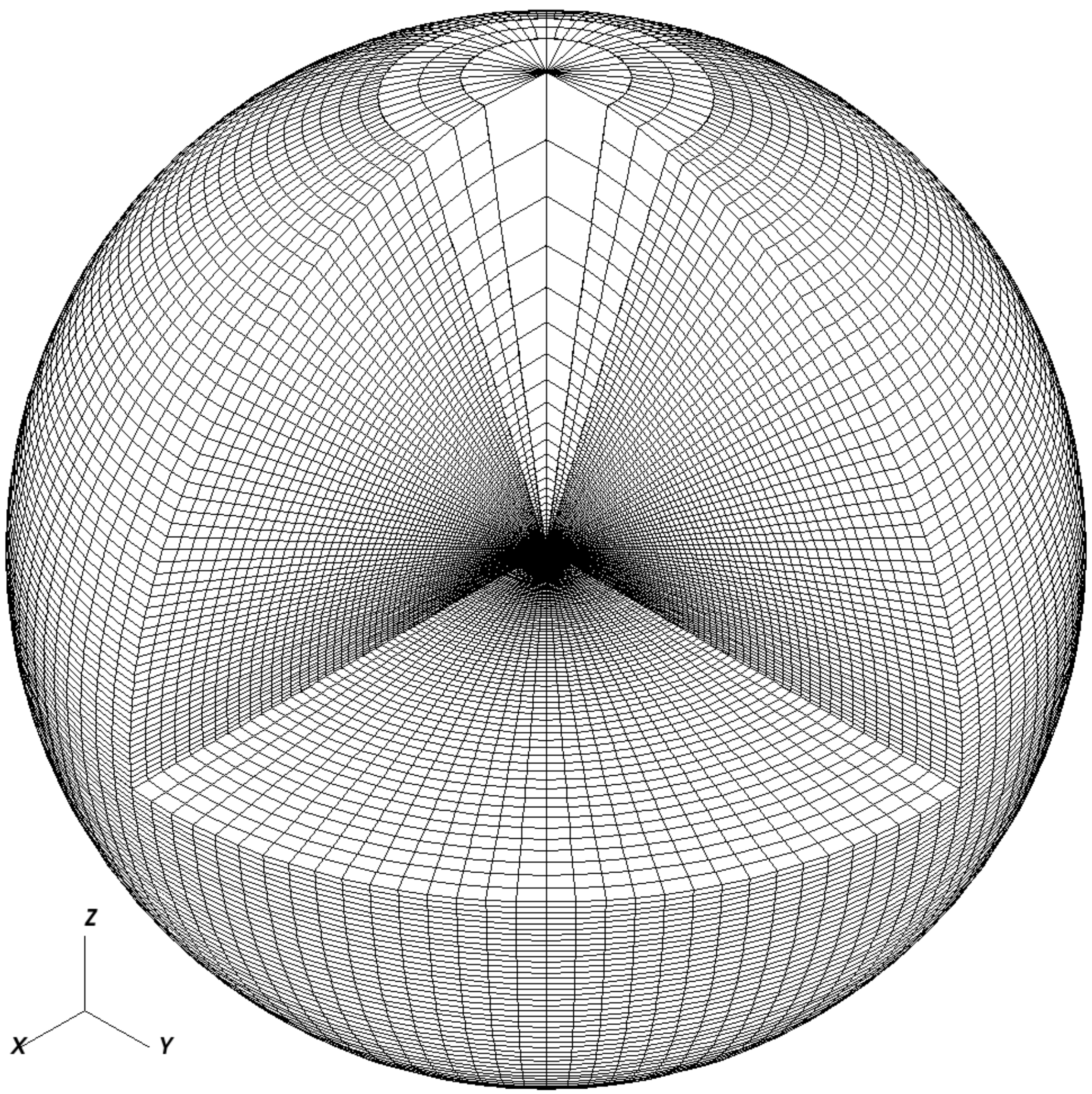
- McKinney & Gammie (2004)

$$P_{\rm jet} \propto \Omega_H^2 \qquad a/M \gtrsim 0.36$$



Spherical-polar grid

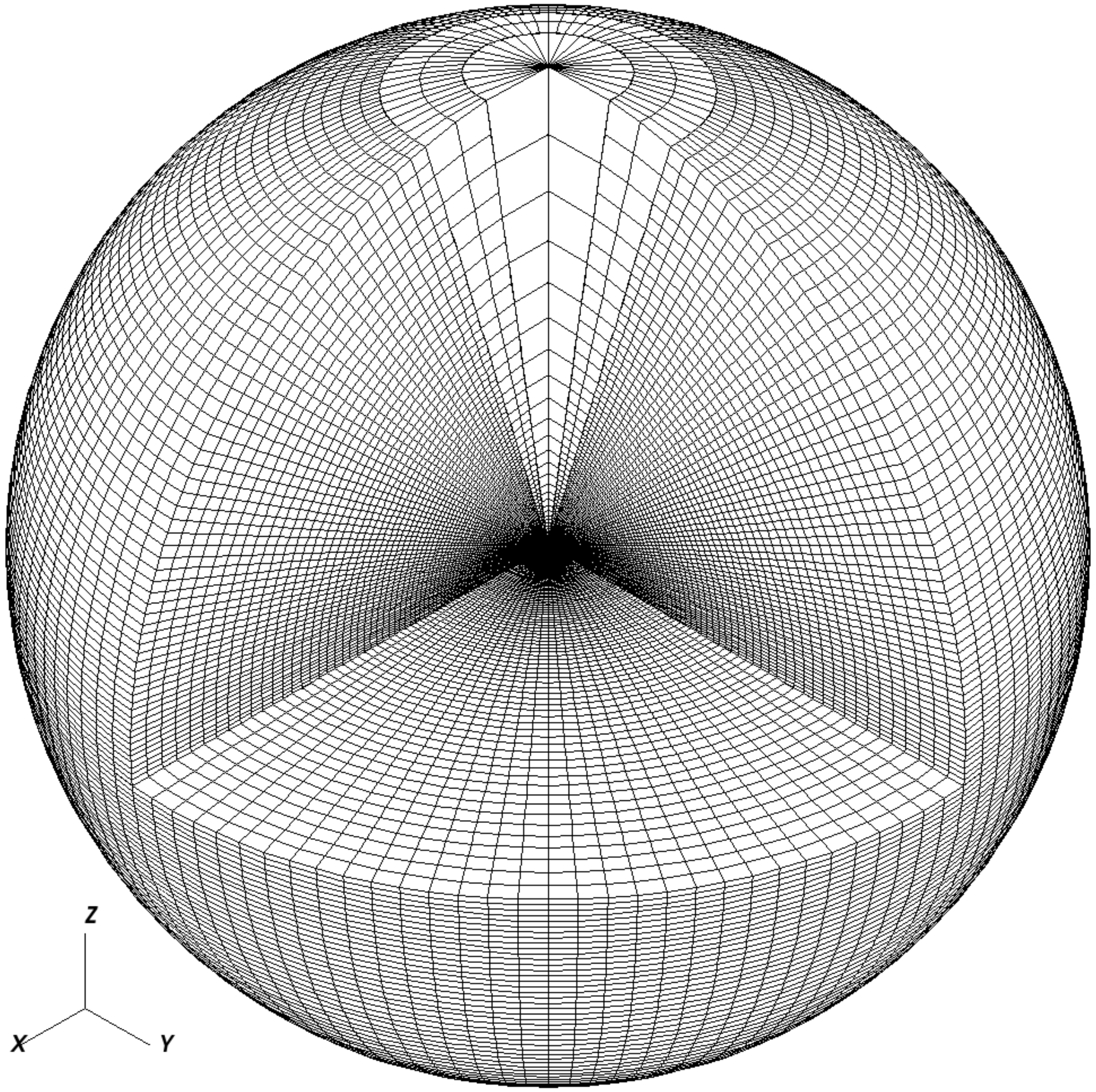
- mathematical singularity at pole
- large variation in zone sizes
  - small zones near pole prohibit reasonable timesteps

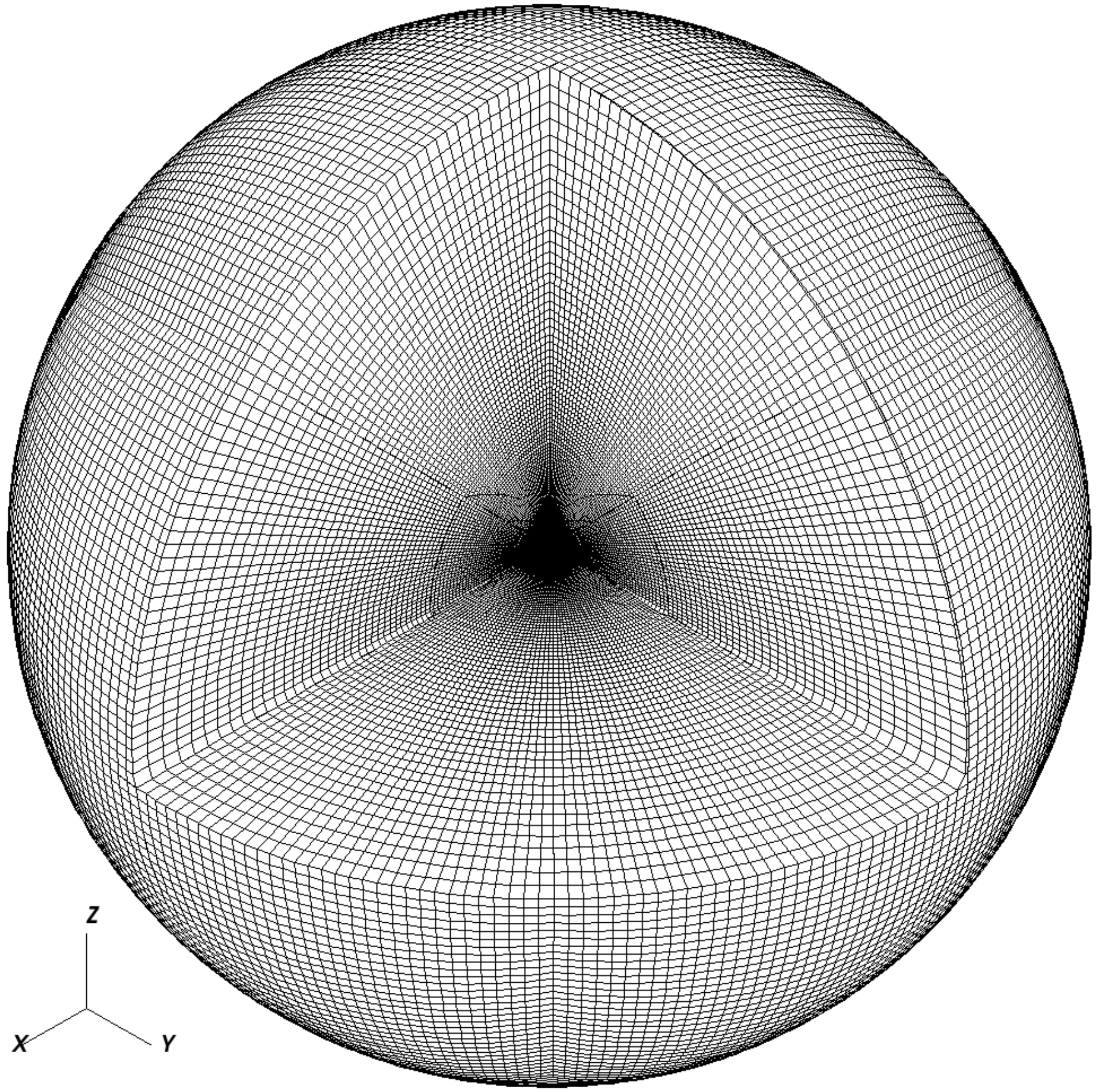


Tilted Black Hole Accretion Disks

Cubed-sphere grid

- no singularities except at origin
- nearly uniform zone sizes





Acknowledgments

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    - LOC and SOC
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